Active

Project #: C-36-688 Cost share #: C-36-395 Rev #: 4
Center # : 10/24-6-R7529-0A0 Center shr #: 10/22-1-F7529-0A0 OCA file #:
Work type : RES
Contract#: IRI-9210925 Mod #: AMENDMENT 003 Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : Y CFDA: 47.070
Main project #: PE #: N/A

Project unit: COMPUTING Unit code: 02.010.300
Project director(s):
GOEL A K COMPUTING (404)894-

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 920615 to 960630 (performance) 960930 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	65,000.00
Funded	0.00	65,000.00
Cost sharing amount		22,618.00

Does subcontracting plan apply ?: N

Title: AN ADAPTIVE APPROACH TO QUALITATIVE MODELING IN DESIGN

PROJECT ADMINISTRATION DATA

OCA contact: Michelle A. Starmack 894-4820

Sponsor technical contact	Sponsor issuing office
LARRY H. REEKER	CHARLETTE L. KENLEY
(703)306-1926	(703)306-1212
NATIONAL SCIENCE FOUNDATION	NATIONAL SCIENCE FOUNDATION
4201 WILSON BLVD.	4201 WILSON BLVD.
ARLINGTON, VA 22230	ARLINGTON, VA 22230

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A NSF supplemental sheet
Equipment title vests with: Sponsor GIT X

Administrative comments -
AMENDMENT NO. 003 EXTENDS THE EXPIRATION DATE TO 6/30/96. THE FINAL REPORT IS NOW DUE 9/30/96.

U

SR481

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 12/02/96

Project No. C-36-688 Center No. 10/24-6-R7529-0A0

Project Director GOEL A K School/Lab COMPUTING

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. IRI-9210925 Contract Entity GTRC

Prime Contract No.

Title AN ADAPTIVE APPROACH TO QUALITATIVE MODELING IN DESIGN

Effective Completion Date 960630 (Performance) 960930 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	N	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other	N	

Comments
LETTER OF CREDIT APPLIES. 98A SATISFIES PATENT REPORT.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other	N
	N

C36-688

College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280
(404)-853-9371
goel@cc.gatech.edu

May 14, 1993

Dr. Su-Shing Chen
Program Director, Knowledge Systems and Cognitive Models
Directorate of Information, Robotic and Intelligent Systems
Division of Computer and Information Science and Engineering
National Science Foundation
1800 G. Street, NW
Washington, D.C 20550

Dear Su-Shing,

This letter is regarding the progress of our research funded by NSF RIA grant C36-688. The grant awards us $60,000 from September 1992 to August 1994, and this letter reports on our progress from September 1992 to May 1993. A major portion of this award is being used to partially support the work of Mr. Sambasiva Bhatta, a graduate student at Georgia Tech working with me, and another major portion will be used to partially support my work during the summers. In accordance with our budget, smaller portions of the award are being used to cover research-related travel, supplies, and computing charges.

Research Accomplishments: Our proposal called for the development of "an adaptive approach to qualitative reasoning in design". The NSF grant has enabled us complete a project called Kritik2 from which our proposal originated, and to initiate another project called Ideal to study the adaptive approach to qualitative reasoning in more detail.

The Kritik2 system integrates experiential case-based and qualitative model-based reasoning for the design of engineering devices such as heat exchanges. Its knowledge of previously encountered devices and their designs is organized in the form of cases. A case is indexed by the functions delivered by the device design stored in the case. Each case contains a pointer to a structure-behavior-function model of the stored device design. The structure-behavior-function (SBF) model of a device specifies the internal causal mechanisms that explain how the structure of the device produces its functions.

Kritik2 designs new devices by retrieving and adapting the design of a device that delivers a similar function. It uses the SBF model of the retrieved device to localize the modifications needed to its design in order to satisfice the functional specification of the desired design. As the system adapts the previous design, it also revises its SBF model to obtain a SBF model of the modified design. It then uses the revised model to qualitatively simulate its output behaviors and thereby verifies whether the modified design will deliver the functions desired of the device. If the design fails, the system attempts to redesign the failed design.

Kritik2 showed how a SBF model of an engineering device can be acquired by adapting the model of a similar device stored in the case memory. For example, the model of a high-acidity Sulfuric Acid cooler may be acquired by first retrieving the case and corresponding model of low-acidity Nitric Acid cooler, and then adapting it using generic modification plans. This work has led us to domain-independent knowledge structures and reasoning algorithms for representing SBF models and acquiring them by model revision. It also led to us to case-based organization of the model memory and heuristics for selecting relevant models from the memory.

The new Ideal project builds on our work on Kritik2 in two ways directly related to the NSF award. First, Kritik2 is limited to reasoning with case-specific SBF models. Ideal investigates the acquisition of abstract functional models of generic causal mechanisms by generalization over the SBF models of specific devices. Second, Kritik2 assumes that case-specific SBF models are complete. Ideal relaxes this assumption and composes SBF models from its design experiences, specifically from design failures. A preliminary version of Ideal is now operational.

Dissemination of Results

The results of the above NSF sponsored research have been reported in a variety of forums including talks at meetings of the IFIP Working Group on Computer-Aided Design and the Cognitive Science Society, chapters in books on AI in Design, and papers in professional magazines and conference proceedings. A journal paper based on this research has been submitted for publication, and a book is under preparation. I have attached a list of all publications since 1992 that are based on the above research. I have also attached the abstracts of some 1993 papers that explicitly acknowledge NSF support for this research.

Thank you.

Yours sincerely,

Ashok K. Goel
Assistant Professor

1. Sambasiva Bhatta and Ashok Goel. Discovering Physical Principles from Design Experiences. In *Proceedings of the 1992 Machine Learning Workshop on Machine Discovery*, Aberdeen, July 1992, pp. 77-81.

2. Sambasiva Bhatta and Ashok Goel. Use of Mental Models for Constraining Index Learning in Experience-Based Design. In *Proceedings of the AAAI-92 workshop on Constraining Learning by Prior Knowledge*, San Jose, July 1992, pp. 1-10.

3. Sambasiva Bhatta and Ashok Goel. Model-Based Learning of Structural Indices to Design Cases. To appear in *Proceedings of the IJCAI-93 Workshop on Reuse of Designs*, Washington D.C., July 1993.

4. Sambasiva Bhatta and Ashok Goel. Learning Generic Mechanisms from Experiences for Analogical Reasoning. To appear in *Proceedings of the Fifteenth Annual Conference of the Cognitive Science Society*, Boulder, Colorado, 1993.

5. Sambasiva Bhatta and Ashok Goel. Model-Based Discovery of Physical Principles from Design Experiences. Submitted to *Artificial Intelligence in Engineering Design, Analysis and Manufacturing*, special issue on Machine Learning in Design.

6. B. Chandrasekaran, Ashok Goel and Yumi Iwasaki. Functional Representation as a Basis for Design Rationale. *IEEE Computer*, pages 48-56, January 1993.

7. Ashok Goel. Integrating Case-Based and Model-Based Reasoning: A Computational Model of Design Problem Solving. *AI Magazine*, 13(2):50-54, Summer 1992.

8. Ashok Goel. Representation of Design Functions in Experience-Based Design. In *Intelligent Computer Aided Design*, D. Brown, M. Waldron, and H. Yoshikawa (editors), pp. 283-308, Amsterdam, Netherlands: North-Holland, 1992.

9. Ashok Goel. Recompositional Analogy: A Model-Based Approach to Design Reuse. In *Notes of the AAAI Spring Symposium on Computational Support for Incremental Modification and Reuse*, Palo Alto, March 1992.

10. Ashok Goel. Design Rationale and Device Redesign. In *Proceedings 1992 DARPA Workshop on Manufacturing Automation and Design Engineering*, Stanford University, June 1992, pp. 410-420.

11. Ashok Goel, Sambasiva Bhatta and Eleni Stroulia. Investigation of Case-Based Design in Multiple Domains. In *Proceedings of the 1992 AI in Design Workshop on Case-Based Design Systems*, Pittsburg, June 1992.

12. Ashok Goel and B. Chandrasekaran. Case-Based Design: A Task Analysis. In *Artificial Intelligence Approaches to Engineering Design, Volume II: Innovative Design,* C. Tong and D. Sriram (editors), pp. 165-184, San Diego: Academic Press, 1992.

13. Ashok Goel and Phyllis Koton. Integrating Case-Based and Model-Based Reasoning. To be published by Academic Press, New York.

14. Sattiraju Prabhakar and Ashok Goel. Integrating Case-Based and Model-Based Reasoning for Creative Design: Constraint Discovery, Model Revision and Case Composition. In *Proceedings of the Second International Conference on Computational Models of Creative Design*, Heron Island, Australia, December 1992.

15. Eleni Stroulia, Murali Shankar, Ashok Goel and Louise Penberthy. A Model-Based Approach to Blame Assignment in Design. In *Proceedings of the Second International Conference on Artificial Intelligence in Design*, Pittsburgh, Pennsylvania, June 1992, pp. 519-538, Kluwer Academic Press.

16. Eleni Stroulia and Ashok Goel. Trade-Offs in Multi-Strategy Reasoning: A Case Study in Experience-Based Design. In *Proceedings of the 1992 AI in Design Workshop on Reusable Design Systems* Pittsburgh, June 1992, pp. 9-21.

17. Eleni Stroulia and Ashok Goel. Generic Teleological Mechanisms and their Use in Case Adaptation. In *Proceedings of the Fourteenth Annual Conference of the Cognitive Science Society*, Bloomington, Indiana, August 1992, pp. 319-324.

Functional Representation as Design Rationale

B. Chandrasekaran, Ohio State University
Ashok K. Goel, Georgia Institute of Technology
Yumi Iwasaki, Stanford University

The design process involves exploring design spaces, simulating and verifying candidate designs, and possibly redesigning and repeating the cycle. The body of information that explicitly records the design activity and the reasons for making choices (and reasons for *not* making some choices) is called the design rationale (DR). As more of the design process gains computational support, some designers are focusing on the tasks of defining the components of DR and casting it into a form that can be recorded and manipulated computationally.

Research is addressing what kinds of information DR should contain and how to express it. In a recent special DR issue of the journal *Human-Computer Interaction*,[1] MacLean et al.[2] proposed a semiformal notation called Questions-Options-Criteria (QOC) to represent the design space. As the space is explored, Questions identify key design issues, Options provide possible answers to these, and Criteria help assess the options. Lee and Lai[3] proposed a language called DRL, which provides a vocabulary for recording design alternatives, the evaluation space and criteria, and the argument structure in which design discussions are conducted.

Lee and Lai make a useful distinction between using DR as

(1) a record of the exploratory activity of the design team (along the lines of the information captured by the QOC formalism) and
(2) an account of how the designed artifact serves or satisfies expected functionalities.

The distinction is essentially one of describing the designer's activity (what alternatives were considered and what choices were made and why) versus describing the artifact's functioning. We consider the use of a representation called Functional Representation (FR) for describing how the device works (or is intended to work). Specifically, we wish to show how FR can be used to capture the causal component of DR. By that we mean the designer's (or the design team's) account of the causal interaction sequence between device components that leads to achieving device functions.

Some of the tasks for which DR can be used are

(1) *Controlling distributed design activity.* In concurrent engineering, the DR for design decisions made by one group can be used by other groups to avoid redundancy of effort and incompatible design choices.

(2) *Reassessing device functions.* During the period of device use, the compo-

Although a design rationale cannot be completely represented, Functional Representation is a good framework for describing causal components because it embodies a theory of how causal stories are understood.

0018-9162/93/0100-0048$03.00 © 1993 IEEE

Learning Generic Mechanisms from Experiences for Analogical Reasoning*

Sambasiva R. Bhatta and **Ashok K. Goel**
College of Computing
Georgia Institute of Technology
Atlanta, Georgia 30332-0280
{bhatta,goel}@cc.gatech.edu

Abstract

Humans appear to often solve problems in a new domain by transferring their expertise from a more familiar domain. However, making such cross-domain analogies is hard and often requires abstractions common to the source and target domains. Recent work in case-based design suggests that generic mechanisms are one type of abstractions used by designers. However, one important yet unexplored issue is where these generic mechanisms come from. We hypothesize that they are acquired incrementally from problem-solving experiences in familiar domains by generalization over patterns of regularity. Three important issues in generalization from experiences are what to generalize from an experience, how far to generalize, and what methods to use. In this paper, we show that mental models in a familiar domain provide the content, and together with the problem-solving context in which learning occurs, also provide the constraints for learning generic mechanisms from design experiences. In particular, we show how the model-based learning method integrated with similarity-based learning addresses the issues in generalization from experiences.

Introduction

Analogy is often believed to play an important role in reasoning underlying innovation and creativity. Analogies can be of different types: within-problem, cross-problem but within-domain, and cross-domain. We are interested in studying cross-domain analogies. Psychological research shows that humans use abstractions in making cross-domain analogies (e.g., Gick & Holyoak, 1983; Catrambone & Holyoak, 1989). Some of the issues of interest then are how reasoning is mediated by the abstractions (shared between the source and target domains) and how those abstractions are learned. We explore the latter issue in the context of the design of physical devices such as electric circuits and heat exchangers. Our goal is to build a computational model that can account for these phenomena and use it to generate testable predictions about designers' behavior.

Goel (1989) has proposed models of generic teleological mechanisms (GTMs), such as cascading, feedback, and feedforward, as one type of abstract knowledge that designers use in case-based design. GTMs take as input the functions of a desired design and a known design, and suggest patterned modifications to the structure of the known design that would result in the desired design. Stroulia and Goel (1992) have shown that GTMs indeed are useful in non-routine adaptive design. But one important yet unexplored issue is how these GTMs are acquired. Our hypothesis is that they are acquired incrementally from problem-solving experiences in familiar domains by generalization over patterns of regularity. For instance, a designer may acquire from examples in the domain of electric circuits a model of cascading, and when and how to cascade a number of similar components together (i.e., to connect multiple components to amplify the overall delivered function). The designer can then use that model for designing in a different domain such as the domain of heat exchangers.

Generalization from experiences raises three important issues. First is the issue of relevance, that is, the issue of deciding what to generalize from an experience. We represent in design experiences a designer's comprehension of how devices work (i.e., how the structure of a design results in its output behaviors). We represent this comprehension as structure-behavior-function (SBF) models and represent the models of GTMs as behavior-function (BF) models. We propose that the problem-solving context in which learning occurs together with the hierarchical organization of the SBF model of the device help determine what to generalize from the model. Further, the SBF models lead to a typology of behavioral patterns over which the generalization process can result in learning GTMs. Second, how far a chosen aspect of the device can be generalized. We show that the similarities in the SBF models of the cur-

*This work has been supported by research grants from ONR (contract N00014-92-J-1234), NSF (grant C36-688), Northern Telecom, Georgia Tech Research Corporation, and a CER grant from NSF (grant CCR-86-19886), and equipment grants and donations from IBM, Symbolics, and NCR.

To appear in the Proceedings of the Fifteenth Annual Conference of the Cognitive Science Society, Boulder, CO, June 18-21, 1993.

Model-Based Learning of Structural Indices to Design Cases*

Sambasiva R. Bhatta and *Ashok K. Goel*

Artificial Intelligence Group
College of Computing
Georgia Institute of Technology
Atlanta, GA 30332-0280

Email: {bhatta,goel}@cc.gatech.edu

Abstract

A major issue in case-based systems is *retrieving* the appropriate cases from memory to solve a given problem. This implies that a case should be indexed appropriately when stored in memory. A case-based system, being dynamic in that it stores cases for reuse, needs to learn indices for the new knowledge as the system designers cannot envision that knowledge. Irrespective of the type of indexing (structural or functional), a hierarchical organization of the case memory raises two distinct but related issues in index learning: *learning the indexing vocabulary* and *learning the right level of generalization*. In this paper we show how *structure-behavior-function* (SBF) models help in learning **structural** indices to cases in the context of case-based design of physical devices. The SBF model of a design provides the functional and causal explanation of how the structure of the design delivers its function. We describe how the SBF model of a design, together with a specification of the task for which the design case might be reused, provides the vocabulary for structurally indexing the design case in memory. We also describe how the SBF model provides the inductive biases for index generalization. We further discuss how model-based learning can be integrated with similarity-based learning (that uses prior design cases stored in case-memory) for learning the level of index generalization. The IDEAL system implements and evaluates the model-based method for learning structural indices to design cases.

1 Introduction

Solving a problem by the case-based method [Riesbeck and Schank, 1989; Kolodner and Simpson, 1989] involves *retrieving* a similar problem from memory, *adapting* its solution to the new problem, and *storing* the new solution so it can be used in future problem-solving situations. A major issue in case-based systems is *retrieving* the appropriate cases from memory to solve a given problem.

*This work has been supported by research grants from ONR (contract N00014-92-J-1234), NSF (grant C36-688), Northern Telecom, and a CER grant from NSF (grant CCR-86-19886), Georgia Tech Research Corporation, and equipment grants and donations from IBM, Symbolics, and NCR.

To appear in the Proceedings of the IJCAI-93 workshop on "Reuse of Designs: An Interdisciplinary Cognitive Approach," Chambery, Savoie, France, Aug. 29, 1993.

C-36-688
2

OMB No. 3145-0058

NATIONAL SCIENCE FOUNDATION
4201 Wilson Blvd.,
Arlington, VA 22230

BULK RATE
POSTAGE & FEES PAID
National Science Foundation
Permit No. G-69

PI/PD Name and Address

Ashok K. Goel
College of Computing
GA Tech Res Corp - GIT
Atlanta GA 30332-0280

NATIONAL SCIENCE FOUNDATION FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org. Larry H. Reeker - IRI

2. Program Name KNOWLEDGE & DATABASE SYSTEMS PROGRAM

3. Award Dates (MM/YY) From: 06/92 To: 06/96

4. Institution and Address
GA Tech Res Corp - GIT
Administration Building
Atlanta GA 30332

5. Award Number 9210925

6. Project Title
An Adaptive Approach to Qualitative Modeling in Design

You are encouraged to submit your Final Project Report electronically **
through the NSF FastLane home page (www.fastlane.nsf.gov). **

This Packet Contains
NSF Form 98A
And 1 Return Envelope

Grant Conditions (Article 17, GC-1, and Article 9, FDP-11) require submission of a Final Project ort (NSF Form 98A) to the NSF program officer no later than 90 days alter the expiration of the rd. Final Project Reports for expired awards must be received before new awards can be made F Grants Policy Manual Section 677).

, or on a separate page attached to this form, provide a summary of the completed projects and technical information. Be o include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

ummary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the t title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent project being described, the following items:

primary objectives and scope of the project
techniques or approaches used only to the degree necessary for comprehension
findings and implications stated as concisely and informatively as possible

PART III - TECHNICAL INFORMATION (for program management use)

eferences to publications resulting from this award and briefly describe primary data, samples, physical collections, tions, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available research community. Provide the NSF Invention Disclosure number for any invention.

to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinion) are true and complete, and text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original f the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a al fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001).

	October 14, 1996
Principal Investigator/Project Director Signature	**Date**

IMPORTANT:
MAILING INSTRUCTIONS
Return this *entire* packet plus all attachments in the envelope attached to the back of this form. Please copy the information from Part I, Block I to the *Attention block* on the envelope.

PART IV -- FINAL PROJECT REPORT -- SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in resonse to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the nformation.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens							1			
B. Total, Permanent Residents	1									
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native										
Asian........................	✓1									
Black, Not of Hispanic Origin.........										
Hispanic........................										
Pacific Islander..................										
White, Not of Hispanic Origin										
C. Total, Other Non-U.S. Citizens					✓1	1				
Specify Country 1. INDIA					1					
2. FRANCE						1				
3.										
D. Total, All participants (A + B + C)	1				1	1	1			
Disabled[3]										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1] Category includes, for example, college and precollege teachers, conference and workshop participants.

[2] Use the category that best describes the ethnic/racial status fo all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3] A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the original peoples of Hawaii; the U.S. Pacific territories of Guam, American Samoa, and the Northern Marinas; the U.S. Trust Territory of Palau; the islands of Micronesia and Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.

FROM

NATIONAL SCIENCE FOUNDATION
FINAL PROJECT REPORT
ENCLOSE FORM 98A

ATTENTION:
TRANSFER INFORMATION FROM BLOCK 1, PART 1 HERE

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

BUSINESS REPLY MAIL

FIRST CLASS MAIL PERMIT NO. 12806 ARLINGTON, VA

POSTAGE WILL BE PAID BY NATIONAL SCIENCE FOUNDATION

NATIONAL SCIENCE FOUNDATION
4201 Wilson Blvd.,
Arlington, VA 22203-9966

Part II: Summary of Completed Project

The primary objective of this research was to develop a computational theory for constructing and acquiring qualitative models of new physical devices by retrieving and revising known device models. The original scope was limited to incremental model revision in the context of evolutionary device design, but the results of our research also cover model construction in creative design.

We conducted this research by iteratively developing (i) a computational theory for model construction in device design; (ii) instantiating the theory in a computer program; (iii) evaluating the program for increasingly realistic problems; and (iv) feeding the results back into (i) to form increasingly sophisticated theories.

Our research has resulted in (a) a new account of device models and a corresponding language for representing the models of a class of devices, (b) a new scheme for indexing, organizing, and accessing a model memory, (c) new algorithms for constructing and acquiring models of new devices by retrieving and revising the known models, and (d) new algorithms that use the constructed models for the tasks of interpretation of design problems, verification of candidate designs, explanation of design failures, and reformulation of problems. A major and important implication is a unification of device models, model memory, model-based reasoning, and model learning.

Part III: Technical Information

This research has led to two distinct but closely related computational theories for constructing and acquiring qualitative models of physical devices. Evolutionary device design forms the context for the first theory called *adaptive modeling.* In the adaptive-modeling theory, qualitative models of new devices are constructed by retrieving and incrementally revising known device models. The second theory, called *model-based analogy*, extends the first theory to creative device design. Qualitative models of new devices, in model-based analogy, are constructed not only by revising the models of similar devices, but also through analogical transfer of generic models.

The origin of these theories lies in our earlier work on evolutionary device design. The key idea in our design work was that device design involves both design experiences (i.e., cases) and device comprehension (i.e., models): while the high-level process of evolutionary design is largely case-based, device models give rise to both the vocabulary and the strategies for addressing the different tasks in the process. The specific hypothesis was that since the task of device design is a function to structure mapping, the inverse structure to function map of old designs may guide their adaptation for achieving new functional specifications. We specified the structure to function map of a device as a Structure-to-Behavior- -to-Function (SBF) model. The Kritik system, developed during 1987-89 at the Ohio State University, instantiated this theory of evolutionary design. Through experimentation with Kritik we found that the SBF models not only give rise to adaptation strategies for modifying old designs and evaluating whether the modified design achieves the desired function, but that they also provide a vocabulary for indexing and organizing the design cases and enabling case retrieval and storage.

Since the model-based process for design adaptation also resulted in a SBF model for the new design, it led us to the theory of adaptive modeling in which SBF models of new devices are constructed by incrementally revising known device models. The Kritik2 system, developed during 1990-92 at Georgia Tech, instantiated the twin theories of evolutionary design and adaptive modeling. Our work on Kritik2 revealed a deep symmetry between evolutionary design and adaptive modeling on one hand and between case-based and model-based reasoning on the other: while device models enable model-based methods for adapting past design cases in evolutionary design, case-based reasoning provides a processing strategy for creating new device designs and constructing new device models. This symmetry enabled us to continue using the same SBF models for both evolutionary design and adaptive modeling. It also enabled us to modify Kritik's algorithms for design creation to obtain Kritik2's algorithms for model construction.

The 1992 NSF RIA award enabled us to continue developing the theory of adaptive modeling. First, we evaluated the theory in a context different from design. In particular, we used Kritik2's SBF models and model adaptation techniques for understanding an English language description of a new device and acquiring a SBF model of the device. The new system, called KA, understands English language descriptions of devices from the popular science book "The Way Things Work" by David Macaulay. For example, it uses a stored SBF model of how a spray can works to understand the description of the workings of the fire extinguisher, and adapts the spray can model to acquire a SBF model of the fire extinguisher. The REU Supplement to the initial RIA award supported the work of Mr. Vinay Pandey on the KA project. From Summer 1994 through Fall of 1995, Mr. Pandey worked with me on entering new cases and models into KA and evaluating the theory of adaptive modeling for acquisition of device models from natural language texts.

In parallel, we constructed a graphical explanatory interface to Kritik2 and thereby developed the Interactive Kritik system. Put together, Kritik2, KA, and Interactive Kritik address the entire cycle of adaptive modeling, from the acquisition of device models from natural language texts, to the use of the constructed models in evolutionary device design and in verifying and explaining the workings of the candidate design. Nathalie Grue wrote her 1994 M.S. Thesis, entitled "Illustration, Explanation, and Navigation of Device Models and Design Processes" based on the Interactive Kritik project.

In addition, we expanded and extended the theory of adaptive modeling to address the issue of creativity in design. In particular, we developed a computational theory of generic (i.e., device-independent) models and model-based analogy. In model-based analogy (MBA), generic models are learned from design experiences in one domain and enable focused transfer of knowledge to design problems that may lie in another domain. We have identified two kinds of generic models that are especially useful in creative device design: generic physical processes and generic teleological mechanisms. A generic physical process captures a pattern of behavioral and causal structure such as heat flow, while a generic mechanism specifies a pattern of functional and causal structure such as feedback.

The Ideal system instantiates this theory of generic models and model-based analogy. It represents generic physical processes and teleological mechanisms as behavior-function (BF) models. When it solves a design problem by constructing a SBF model for the desired device, it uses the new SBF model, together with similar SBF models in its analog memory, to abstract and acquire generic BF models. The generic models provide an enhanced set of design adaptation and model construction strategies that range from tweaking design parameters to instantiation of generic models to analogical transfer of generic models across device domains. The cross-domain transfer of generic models leads to topological modifications that apparently are a characteristic of creative design. Dr. Sambasiva Bhatta wrote his 1995 Ph.D. Dissertation, entitled "Model-Based Analogy in Innovative Device Design," based on the Ideal project.

Dissemination of Information

This NSF funded research has led to nearly a dozen presentations at major conferences and workshops, including the bi-annual International Conferences on AI in Design, the annual conferences of the Cognitive Science Society, and the annual Qualitative Reasoning Workshops. It has also lead to nearly a score of major papers in journals, professional magazines, and proceedings of formally refereed conferences:

B. Chandrasekaran, A. Goel and Y. Iwasaki. Functional Representation as a Basis for Design Rationale. *IEEE Computer*, 26(1):48-56, January 1993.

S. Bhatta and A. Goel. Learning Generic Mechanisms from Experiences for Analogical Reasoning. In *Proc. Fifteenth Annual Conference of the Cognitive Science Society*, Boulder, Colorado, July 1993, pp. 237-242, Hillsdale, NJ: Lawrence Erlbaum.

J. Pittges, K. Eiselt, A. Goel, A. Gomez, K. Mahesh, and J. Peterson. KA: Integrating Natural Language Processing and Problem Solving. In *Proc. Fifteenth Annual Conference of the Cognitive Science Society*, Boulder, Colorado, July 1993, pp. 818-823, Hillsdale, NJ: Lawrence Erlbaum.

N. Grue. Illustration, Explanation, and Navigation of Device Models and Design Processes. M.S. Thesis, College of Computing, Georgia Institute of Technology, June 1994.

J. Peterson, K. Mahesh and A. Goel. Situating Natural Language Understanding in Experience-Based Design. *International Journal of Human-Computer Studies*, 41: 881-913, 1994.

S. Bhatta and A. Goel. Model-Based Discovery of Physical Principles from Design Experiences. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Special Issue on Machine Learning in Design, 8(2):113-123, May 1994.

S. Bhatta, A. Goel and S. Prabhakar. Innovation in Analogical Design: A Model-Based Approach. In *Proc. Third International Conference on Artificial Intelligence in Design*, Lausanne, Switzerland, August 1994, pp. 57-74.

A. Goel and S. Prabhakar. A Control Architecture for Redesign and Design Verification. In *Proc. 1994 Australian-New Zealand Intelligent Information Systems Conference*, Brisbane, Queensland, Australia, Nov. 29 - Dec 2, 1994, pp. 377 - 381.

S. Bhatta. Model-Based Analogy in Innovative Device Design. Ph.D. Dissertation, College of Computing, Georgia Institute of Technology, December 1995.

S. Bhatta and A. Goel. Model-Based Indexing and Index Learning in Analogical Design. In *Proc. 1995 Seventeenth Annual Conference of the Cognitive Science Society*, Pittsburgh, July 22-25, 1995, NJ, Hillsdale: Erlbaum.

S. Prabhakar, A. Goel and S. Bhatta. Adaptive Modeling in the Design of Interactive Devices: Towards a Theory of Engineering Invention. In the *Proc. Third International Conference on Computational Models of Creative Design*, Heron Island, Australia, December 1995, pages 267-301.

S. Bhatta and A. Goel. From Design Cases to Generic Mechanisms. *Artificial Intelligence in Engineering Design, Analysis and Manufacturing*, Special Issue on Machine Learning 10:131-136, 1996.

S. Prabhakar and A. Goel. Learning about Novel Operating Environments: Designing by Adaptive Modeling. *Artificial Intelligence in Engineering Design, Analysis and Manufacturing*, Special Issue on Machine Learning, 10:136-142, 1996.

A. Goel and E. Stroulia. Functional Device Models and Model-Based Diagnosis in Adaptive Design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 10:355-370, 1996, Special Issue on Functional Reasoning.

A. Goel. Adaptive Modeling. In *Proc. Tenth International Workshop on Qualitative Reasoning*, Lake Tahoe, California, May 1996, pages 100-107.

A. Goel, A. Gomez, N. Grue, W. Murdock, M. Recker, and T. Govindaraj. Design Explanations in Interactive Design Environments. In *Proc. Fourth International Conference on AI in Design*, Palo Alto, June 1996.

A. Goel, K. Mahesh, J. Peterson and K. Eiselt. Unification of Language Understanding, Device Comprehension and Knowledge Acquisition. In *Proc. 1996 Cognitive Science Conference*, San Diego, July 1996.

T. Griffith, N. Nersessian and A. Goel. The Role of Generic Models in Conceptual Change. In *Proc. 1996 Cognitive Science Conference*, San Diego, July 1996.

Software Products

As briefly described above, the NSF award has partially supported the development of three prototype software systems: Interactive Kritik, KA, and Ideal. All three systems evolve from the original Kritik2 system developed earlier, and run on CommonLisp/CLOS. Interactive Kritik contains about a dozen design cases and device models in the domains of simple electrical circuits and heat exchange devices. KA too contains about a dozen cases and models from the domains of heat exchange systems and pressure release chambers. Ideal contains about three times as many cases and models from the domains of heat exchange devices, electrical circuits, operational amplifiers, and gyroscopes.

The Kritik2 system, which we have tested most extensively, is now available in the public domain. Dr. S. Prabhakar, a faculty member with the University of Technology in Sydney, Australia, recently ported Kritik2 to his laboratory for further experimentation and development. Researchers from KSL at Stanford University, NIST, and Boeing Space and Defense, too have expressed an interest in using Kritik2.